Exhibit B

INTRODUCTION TO MICROWAVE CIRCUITS

Radio Frequency and Design Applications

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either a full nonlinear analysis needs to be done or several other types of approximate analysis can be performed. If the ac signal is small with respect to the dc signal, then a small signal analysis using differential ac analysis is often performed. The circuit is analyzed at a particular dc value and then the ac signals are added to the dc values using differential or small signal analysis of the circuits. These techniques are usually familiar to the microwave engineer. However, when the ac signal is large with respect to the dc signal values, another technique is followed if the ac signal does not appreciably change the dc operating conditions. This is particularly applicable for circuits that have charge storage devices in them. One of the charge storage devices is the PIN diode. The amount of charge stored in the device is determined by small signal dc analysis and the large signal performance is performed about that small signal dc condition under the assumption that the small signal dc value does not change over a cycle of the ac large signal. The validity of this assumption needs to be checked just as the small signal assumption is checked in the ac analysis of small signal nonlinear circuits. This should become evident in the discussion of the PIN diode.

12.2.2 Diode Packages

Two terminal diode devices are often inserted in a microwave package called a *pill*. The pill diode comes in various sizes and sometimes comes with prongs and sometimes without prongs. There are several versions of this package. However, the parasitics are all similar and need to be incorporated into a design. Figure 12.1 shows a typical diode package. This is shown for the purposes of showing the various parasitics that are associated with a diode package. Other types of packages exist. When the leads directly attach to the diode as shown in Figure 12.2, the inductance between the package capacity and diode disappears. The lead inductance still exists but the parasitic package capacity appears almost directly across the device. The diode capacity is also reduced with this construction.

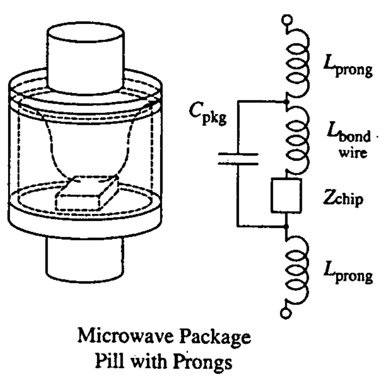

Figure 12.1 Diode Package and its parasitics.

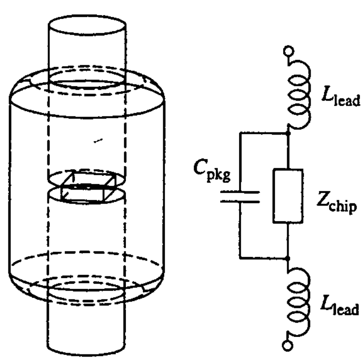

Figure 12.2 Diode package formed by leads.

12.2.3 Varactor Diode

A varactor (variable capacitor) diode is a semiconductor junction diode. The parasitic series resistance of a varactor diode is of primary consideration in maximizing the Q of the diode. The depletion region of the semiconductor junction acts as a capacitor. The dc voltage across the diode determines the depletion width and thus the depletion capacitance of the varactor. The rf voltage across this depletion region must be small with respect to the dc voltage across the diode if harmonic generation is to be minimized. However, often, harmonic

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generation is the desired result in frequency multiplier circuits. A schematic of a varactor chip is shown in Figure 12.3. The chip inductance is not shown. That inductance is often smaller than the inductance of the package that the chip is inserted into. The figure also assumes that the P region is doped much higher than the N region so that the depletion region is primarily in the N region. The depletion region capacity of a varactor diode is given by:

$$C \approx \frac{K}{(V + V_{bi})^s} \qquad s = \frac{1}{m+2}$$

where V_{bi} is the built-in potential and V is assumed to be a back bias voltage across the diode. In the n side of the region of the junction, the diffusion profile, and thus the charge variation of the depletion region is often approximated by:

$$n(x) = Bx^m$$

where m is the diffusion slope parameter used in the capacity slope equation. A $\log(C)$ versus $\log(V + V_{bi})$ plot will have a slope s given by:

$$\log(C) = \log(K) - s\log(V + V_{bi})$$

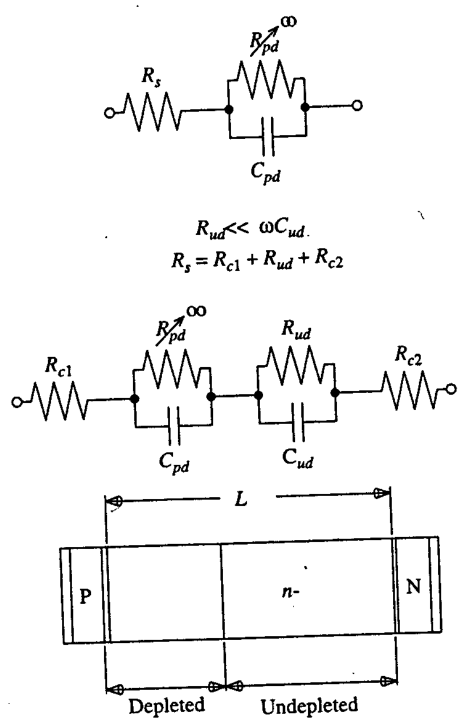

Figure 12.3 Varactor diode equivalent circuit.

An abrupt junction diode has $m = 0$, $s = 1/2$, a linear graded junction has $m = 1$, $s = 1/3$, and a hyperabrupt junction has $m < -1$, $s > 1$. Each of these types of diodes has applications in different types of rf circuits.

A typical varactor diode used in the 100-MHz to 10-GHz frequency range would have package inductances on the order of 0.5 nH, package capacities of several tenths of picofarads, and series resistances of less than one-half ohm. For example, a GaAs abrupt junction varactor might have a Q of 250 at 1 GHz and a junction capacity of 4 pF at 7 V back bias. This would give:

$$R_S = \frac{1}{(250)(2\pi 10^9)(4. \times 10^{-12})} = 0.16\Omega$$

One limitation on the frequency where the varactor can be used is the resonance caused by L_{pkg} in series with the series combination of the junction capacitance and C_{pkg}. For a $C_{pkg} = 0.5$ pF, $L_{pkg} = 0.5$ nH, the above varactor diode would be used at frequencies much below 11 GHz. However, the mounting structure for the diode package can easily add 1 pF of parasitic capacity if care is not given to the structure. This capacity will be in parallel with C_{pkg} and can limit the upper frequency over which the packaged diode is useful.

Some varactor diodes used for harmonic generation are hybrids between pure varactor and PIN diodes. These hybrid diodes are often called *bimode* diodes. The large capacity variation and large forward voltage swings available with bimode diodes combine to provide high-power multipliers [6]. The function of a PIN diode used as a switch and not for harmonic generation will be discussed next.

12.2.4 PIN Diode Characteristics

The PIN diode comes from considering three different doped regions of a semiconductor put together. These are the p region (P), the intrinsic region (I), and the n region (N). Typically, the N region is the substrate region and the I region and P region are grown on top of the substrate. The diodes can also be fabricated in an *NIP* format where the structure is upside down. The diodes are generally fabricated vertically and often by epitaxial growth. The high breakdown voltage 1N4007 diode has many of the characteristics of a PIN diode. It has a long low doped region with higher doped contacts. At lower frequencies, this diode can often be used to demonstrate many of the features of a PIN diode. A word of caution is in order. The 1N4007 diode is a generic diode and is not manufactured to an rf PIN diode specification. Therefore, a specific diode from a specific vendor may not act the same as a specific diode from another vendor.

12.2.4.1 General Diode Considerations. This section discusses some of the properties of PIN diodes. The PIN diode is often used as a switch. The switch may be used for low-power or high-power signals. If it is used for high-power signals, the rf current through the diode can be many times larger than the dc bias current through the diode. The diode can also withstand rf voltages across it that cause the net voltage across the diode to be very large in the forward direction. The familiar exponential V-I characteristic of a diode is the equilibrium or steady-state characteristic of a diode. Under large voltage swings associated with rf switching, the transient V-I characteristics of a diode are much different. However, the reverse breakdown of a diode under transient conditions is very close to the dc breakdown of a diode since breakdown is a very fast phenomenon. The objective of this discussion is to determine how much power can be safely switched by the PIN diode. The analysis in this section will be a first-order analysis and is good enough for many calculations. A PIN diode with an undepleted I region is depicted in Figure 12.4. As shown in Figure 12.4, the PIN diode has a P region, an I region, and an N region. The I region may be short or long relative to diffusion profiles of the P and N regions depending on which type of diode is preferred. The I region of the diode may be fully depleted (and thus containing no free carriers) or partially depleted (and thus containing free carriers) depending on the diode structure. In order to understand the equivalent circuit of each region, consider a block of semiconductor as shown in Figure 12.5. If the carriers that exist in the volume of material shown in Figure 12.5 are not moving at a velocity-saturated velocity, the current I across the volume is:

$$I = JA = Aq(v_n n + v_p p) = AqE(\mu_n n + \mu_p p)$$

where J is the current density, A is the cross-sectional area, q is the magnitude of the electronic charge, n is the electron concentration, p is the hole concentration, v_n is the electron velocity, v_p is the hole velocity, E is the electric field, μ_n is the electron mobility, and μ_p is the hole

Figure 12.4 PIN diode cross section
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Figure 12.5 A block of semiconduct

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